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EXPERIMENTS IN VISUAL LOCALIZATION

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INTRODUCTION AND CONCLUSIONS

When we change our direction of gaze from one point to another in the visual field of view the position of the image of the field at our retinas is correspondingly changed. Nevertheless we do not normally see any movement or displacement of the visual field or of objects in the field as we generally do when the direction of gaze is held steady and either the entire visual field or objects in the visual field are moved. Several important aspects of this mystery regarding how stability of our perception of space is maintained when we turn our eyes have recently been clarified. The main findings leading to the clarification have been reported elsewhere (Matin, Picoult, Stevens, Edwards, Young and MacArthur, 1980, 1982), and it will be the task of this chapter to show how these results do yield an important aspect of the solution. This portion of the solution will be stated below in the form of 4 conclusions.

Since Helmholtz (1866) originally proposed that the "effort of will" employed in changing the direction of gaze is taken into account in judging whether the changed retinal image location of objects is due to the eye movement produced by the will's effort or by movement of the objects themselves, several alternative sources of extraretinal eye position information (EEPI) have been proposed as the basis for perceptual stability. However, the algebra of the cancellation mechanism suggested by Helmholtz (as shown in Fig. 1) has been common to all of the proposals. The conclusions drawn from the more recent work do not decide on the

source of EEPI but do demonstrate the existence of cancellation and of important constraints placed on the operation of cancellation by the presence of illuminated and structured visual fields:

Fig. 1

Conclusion 1: For an observer viewing in a normally-illuminated and structured visual field EEPI-driven cancellation mechanisms (Fig. 1) are not normally involved in the determination of visual localization of objects in the visual field either relative to each other or relative to visual norms such as the perceived eye-level horizontal or perceived median plane.

Conclusion 2: In darkness EEPI-driven cancellation mechanisms play a central role in determining visual localization of objects relative to visual norms.

Conclusion 3: EEPI-driven cancellation mechanisms play a central role in intersensory localization (e.g. matching locations of sound and light) in either darkness or light if visual capture of the sensory information regarding location via the other modality is prevented.

Conclusion 4: In normally-illuminated visual fields EEPI is not suppressed. Nor is the output of the cancellation mechanism. However, what is suppressed in the normally-illuminated field is the involvement of EEPI in visual localization. Thus under some conditions the EEPI-driven cancellation mechanism may remain

involved in other aspects of perception such as a comparison of localization of auditory and visual targets athough it has no influence on visual localization.

The experiments which have led to these conclusions were carried out on subjects who were made paretic (partially paralyzed) by systemic injections of curare (d-tubocurarine). The partial paralysis was thus produced at the neuromuscular junctions of peripheral cholinergic musculature (Goodman and Gilman, 1977) which includes the extraocular muscles there was no influence on cognitive abilities.[1] The influence on the extraocular musculature produced a dosage-dependent limitation on the range of ocular positions; within this reduced range there was no increased difficulty (no increased "sense of effort") in fixing the gaze in any assigned direction..

THE ORIGINAL OBSERVATION: PERCEIVED CHANGE IN ELEVATION

The concommitant influences of the paresis on visual localization were substantial. However, they only occurred in

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[1]See Ref. #2, Matin et al 1982 for details regarding curarization.

darkness[2] Thus, in normal room illumination with the eyes in any given direction of gaze[3] everything appeared perfectly normal and indistinguishable from the appearance in the normal state. However, as soon as the room lights were extinguished and all was in darkness except for a single fixation target at eye level that remained illuminated, this target appeared to move slowly in the direction of the (invisible) floor. When it reached a position near or at the floor movement essentially ceased and the target appeared to remain at the floor. Surprisingly, when the room was

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[2]When voluntary saccades are performed during partial paralysis a brief transient "jumping" of the visual field is typically observed. However, after this the visual field appears indistinguishable from its appearance before the saccade; it also appears indistinguishable from its appearance in the unparalyzed state. We have not yet determined which of the following two explanations for "jumping" is the correct one: [a] it is due to a transient failure of an EEPI-driven cancellation mechanism in conjunction with a transient failure of Type A suppression [Matin, 1981; 1982; also see below]. [b] It is related to the eye's failure to reach the saccade's goal at the end of the initial saccade; immediately subsequent saccades carry it to the goal; and the visual field then appears normal; the "jump" itself corresponds to the discrepancy between the saccade's goal and the eye's position at the end of the initial paralysis-shortened saccade. Explanation [b] is based on related observations made during parametric adjustment of normal eyes: during a saccade from an original fixation point A to a goal at point B both A and B are extinguished and point C - a target between A and B is turned on. On the first such trial "jumping" of the target goal is observed, with immediately subsequent saccades the observer "corrects" eye position to point C, and everything looks normal. After several such trials the observer's attempt to reach B leads to reaching C in a single saccade; when this occurs no jumping is seen and if the procedure is carried out in darkness the observer is not aware that his saccade has not carried his eye to B.

[3]All viewing was monocular [eye patch over the other eye] during paralysis. The first sign of drug action was an uncontrollable diplopia; this appeared before the subject felt any other sign of weakening.

reilluminated the fixation target immediately appeared as it had originally -- at eye level -- and the room appeared perfectly normal. This sequence of observations could be repeated as often as desired with successive reilluminations and extinctions of illumination.

On the possibility that the visually perceived drop of the fixation target was produced because extinction of illumination resulted in the observer's feeling that his body was tilted backwards we had him extend his arm and point his finger in the direction of the horizontal. Although he could barely raise his arm, the finger always pointed as accurately in the direction of the horizontal in darkness as it did in the fully illuminated room.

A second possible explanation of the illusory drop was also readily eliminated: it was possible that the perceived drop was due to a loss of fixation in darkness which produced an eccentric retinal placement of the fixation target. Since perception of visual direction during involuntary eye movements is not compensated by an EEPI-driven cancellation mechanism (Matin, Pearce, Matin, and Kibler, 1966; Matin, Pola, Matin, and Picoult, 1981), the localization errors might be consequent on such involuntary eye movements. But identical observations resulted when we substituted a 2^{o} transilluminated "E" for the original 9' circular transilluminated fixation target. Since the E always remained clear and sharp even when it appeared near the floor in darkness, and since clarity of the E drops off rapidly with retinal eccentricity so that at eccentricities between 2^{o} and 5^{o}

the E becomes unresolvable, it was possible to conclude that fixation of the single target remained at the central fovea in darkness and loss of fixation was not involved in producing the dramatic drop.

We began zeroing in on the basis for the illusion as soon as we changed the direction of tilt of the observer's head-and-body relative to horizontal. The original observations described above had been made with the head tilted back and β (Fig. 2) set at about 20°. When β was set at a smaller angle, the perceived drop of the fixation target did not proceed as far, and when the head was tilted forward, instead of appearing to drop the light appeared to rise to a position near the (invisible) ceiling when room illumination was extinguished.

Although this result was absolutely clear, it did not yet yield an unequivocal interpretation. Changing the tilt of the subject's head-and-body also required that he change the position of his eye relative to his head in order to foveally fixate the fixation target (which itself was always at physical eye level). Thus, we could not yet decide whether what was important was the variation in the angle of the head-and-body relative to gravity (angle β) or the variation of the angle of the eye in the head (angle α). Separating these two possibilities was effected by the next set of observations:

With the head-and-body fixed at a given value of β, the single target visible in darkness was placed at different heights above and below the physical eye level of the observer. For each such setting the room was illuminated and the illumination was

extinguished while fixation was maintained on the single target. We now discovered that the more α was above some particular value the larger was the distance of the apparent ascent of the fixated target; values of α below this particular value produced an apparent descent, and the more α was below this particular value the greater was the descent. At the particular setting of α above which ascent occurred and below which descent occurred, neither ascent nor descent occurred. For this reason this position was called the "no-illusion direction" (NID).

Interestingly enough, the NID remained fixed although the tilt of the subject's head-and-body (angle β) was itself changed, and this strongly implied that it was the magnitude of angle α that was the important variable producing the apparent change in position of the fixation target between normal illumination and darkness. At this point more extensive quantitative measurements of the phenomenon seemed to be required in order to further isolate the controlling variables and this became our next goal.

QUANTITATIVE MEASUREMENTS OF PERCEIVED EYE-LEVEL

Two sets of quantitative experiments proved that only the angle α influenced the perceived change in elevation, and that neither angle β nor the physical height of the target itself was involved. In both of these experiments angle α was experimentally set at various values, and at each the subject set *a light to the elevation which he perceived* to be horizontal eye-level.

a. One-Light Experiment

In this experiment the subject's head-and-body were set at a particular value of β, and with fixation maintained on the single target visible in darkness, the subject instructed the experimenter to adjust the target's elevation until it appeared to lie at the eye-level horizontal. This was repeated with β set at each of a number of different values. With β set so that

head orientation (Fig. 2c) was pointed in a direction considerably above the physical horizontal, the visual target also had to be set considerably above the physical eye-level horizontal in order to appear to lie at eye-level. Lowering the head-and-body (lower β values) led to a monotonic lowering of the physical elevation of the setting. From this observed relation we extracted the relation between α and the error in the observer's setting from true eye-level. This latter relation was linear with a substantial negative slope; with α directed further upward, the observer's setting of the perceived eye-level horizontal (and therefore the error) was further downward. Although the direction of this relation between α and the subject's setting was predicted from the previous measurements of the NID, the simple linear relation could not have been predicted from the NID measurements.

Although these measurements are extremely informative, by themselves they do not resolve the question regarding whether β or α is the critical variable determining the illusory change in perceived eye-level horizontal. They do mesh well with the previous meaurements of the NID. But in order to resolve the

isssue regarding the critical variable it was necessary to carry out the two-light experiments to be described in the next section.

b. Two-Light Experiment

The reason that the one-light experiment did not permit resolution of the question regarding the critical variable controlling the illusory change of visual localization is that although the experimenter could vary β systematically he could not simultaneously hold α constant since for any given value of β, α was varied with and was determined by the elevation at which the observer set the fixated target.

The two-light experiment to be described provides simultaneous control of β and α, and completely resolved the issue: Only α -- and not β -- determines the magnitude of the illusory localization change.

After a particular value of β was experimentally set by adjusting the position of the head and body, a particular value of α was fixed experimentally by setting a visual fixation target to a particular elevation. With α and β thus fixed, a second visual target was introduced along the same vertical line as was the fixation target. The elevation of this second target was adjusted according to the subject's instructions to appear at the eye-level horizontal. Keeping β fixed at this value, the value of α was then changed by adjusting the elevation of the first target and a new setting of the second target was made

according to the subject's instructions. Thus we were able to determine directly the relation between the angle of gaze relative to the head (α) and the physical elevation of the perceived eye-level horizontal that held with head-and-body position fixed. This relation is shown in Fig. 2a and 2d. This relation was unchanged at several different values of β, and thus establishes that β is uninvolved in the illusion of localization, and that the variation of the illusion is based on variation of the position of the eye in the head -- angle α.[4]

Fig. 2

ILLUSORY CHANGES IN VISUAL LOCALIZATION OF THE MEDIAN PLANE

The eye-level horizontal is a direction in space that is defined in relation to gravity. Thus eye position in relation to the head is not sufficient to define it as visual direction in physical space; some information about head position relative to gravity must also be involved. Apparently -- as expected -- the

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[4]In the two-light experiment the light set to perceived eye-level horizontal was imaged at retinal locations whose eccentricities differed as α and β were changed. Although distortions between retinal distances and perceived distances could thus influence the relation obtained between α and perceived eye-level horizontal, the fact that the latter relation was uninfluenced by β implies that such distortions had no important influence on our results. A further basis for this conclusion lies in the fact that the relation between α and perceived eye-level horizontal obtained in the one-light experiment was indistinguishable from those in the two-light experiment when both were obtained under the same level of curare.

partial paralysis did not modify the head position information (deduced above from the invariance of the relation between α and perceived eye-level horizontal under variation of β), an interesting result by itself, and so the illusory effects in the previous section appear to be entirely due to influences of the paralysis on EEPI. It is nevertheless desirable to be able to measure visual localization for a case in which head position relative to physical space (angle β) was not involved in the judgment at all but in which EEPI was. A number of possibilities exist for this. We chose to measure the visually perceived location of the erect subject's own median plane in darkness for this purpose.

Perceived median plane measurements were made by setting a visual target to the horizontal position at physical eye level designated by the subject while the horizontal eccentricity of his gaze direction was determined by a fixation target set at eye level. A result analogous to the one obtained for the eye-level measurements was obtained: Increasing gaze eccentricity leftward from a "zero point" produced perceived median plane settings that increased to the right of the true median plane: increasing gaze eccentricity rightward yielded settings that increased leftward: the relation is linear. Results of one experiment are shown in Figs. 2b and 2e.

This experiment was carried out in two variations: (1) Since the fixation target appeared to drop to the floor with β set in the more comfortable positions, the settings to the median plane were made with a light at true eye-level that appeared near the

floor. (2) With β set in in the same direction a second set of measurements was made with the fixation target that determined horizontal gaze direction set at an elevation above the true eye level for which the target appeared to lie at eye level. The results of the two variations were indistinguishable. The results shown in Fig. 2 are with variation (1).

INFLUENCE OF LEVEL OF PARALYSIS

Increasing dosage level produced an increase in the slope of the relation of error of localization to eccentricity of eye position for both eye-level horizontal and median plane settings.

One set of such data is shown in Fig. 3. Of considerable interest is the fact that the slopes (not shown) for both settings for a given individual were extremely similar; the change of slope with dose level was also extremely similar for both settings.

Fig. 3

A DESCRIPTIVE 3-PARAMATER MODEL OF THE INFLUENCE OF PARALYSIS ON VISUAL LOCALIZATION AND OCULOMOTOR CONTROL

Fig.4 provided a description encompassing the 4 main features of the consequences of experimental partial paralysis of the extraocular muscles that we measured. Our present thinking also leads us to believe that this model will apply to naturally occurring pathological paretic states such as those that occur in myasthenia gravis and in other pathological states involving

ophthalmoplegia, and we are currently carrying out such research.

Fig. 4

The four main features encompassed by Fig. 4 are:

1- The center of coordinates for the relation between direction of the perceived eye-level horizontal and vertical gaze direction (Fig. 4a) has been set at the no-illusion point (NID). Similarly for the relation between perceived median plane and horizontal gaze direction (Fig.4b). For gaze directions above the NID, (Fig.4a) the perceived eye-level horizontal deviates downward relative to its direction when gaze direction is at the NID. A similar relation holds for the perceived median plane and the horizontal deviations of gaze direction from the NID (Fig.4b).

What relations the NID has to other measures of the "position of rest of the eyes" or primary position of gaze have not yet been dealt with experimentally. It is clear however that some simple relations should be expected. Nor have we yet dealt with the question of whether or not the NID for perceived eye-level is invariant with changes in horizontal gaze direction; or whether or not the perceived median plane is invariant with vertical gaze directon. Nor have we dealt with the further important question of whether or not the NID is invariant with level of paralysis or not. In Fig.4 we do assume invariance; this assumption does not influence the main line of the present treatment. But the question has yet to be dealt with

experimentally.

2- The results of all of the experiments we have done strongly suggest that the relation of visual localization to gaze direction of either perceived median plane or eye-level is linear at any given dosage level up to near-total paralysis, and that the slope of the linear relation is the same on both sides of the NID. Our measurements (cf; Fig. 2) have not yet been sufficiently precise to deal with the possibility of small deviations from linearity although large deviations are clearly ruled out.

3- The experimental results are clear in establishing the fact that increase in dosage level produces an increase in illusion magnitude and this is represented in Fig. 4 by the increase in slope. It is also clear that the increased dosage has similar influences on the relations involving both directions of change of gaze direction, and is thus implied in Figs. 4a and 4b. The separation between the functions for different dosages in Fig. 4 depends on the specific quantitative relation of dosage to level of paralysis. We have not yet explored this sufficiently to be able to provide any further information on it beyond data such as in Fig. 3

4- Most importantly displayed in Fig.4 is the observation that the paretic state involves a reduction in the range of eye positions that can be attained and that the reduction is greater with an increase in dose level (dashed lines mark the endpoints of gaze). This decrease in the range of possible eye positions with increase in dose is correlated with the increase in the

slope of the relation of visual localization to eye position.

These results suggest the following simple expression relating eye position and illusion magnitude:

$$I=(K-1)\alpha$$

where I is illusion magnitude specified as the negative of the ordinate value in Fig.4, α is direction of gaze specified as an angle of the eye relative to the head and k-1 is the slope of a straight line in Fig. 4.

We do not yet know the quantitative function that describes the way in which the limits of gaze change with dosage. This is the function that determines the shape of the dashed curves in Fig.4. Several aspects of the observations suggest that the functions will be approximately straight lines over the large region of α as shown. These aspects of the observations are as follows: (1) At the most extreme eye position possible at any given level of paralysis the illusion magnitude was larger if this extreme eye position was less deviant from NID. Given the increase of the absolute value of the slope of the main straight line relations in Fig.4, this fact tells us that the dashed lines must at least all increase monotonically from left to right in Fig. 4. (2) A second aspect of the observations is that the magnitude of the illusory change in visual localization in any given curarized state never exceeded the difference between the endpoint of the range of eye positions in the normal state and the endpoint in the curarized state. Indeed, it appeared that this reduction in the eye position limit was approximately equal

to the illusion magnitude when the eye was at this limit.[5]

This description suggests a simple interpretation: The curare-induced reduction in neuromuscular efficiency required that in order for the eye to reach a given position the pattern of motor signals to the muscles must be equivalent to the pattern employed to turn the unparalyzed eye to a more eccentric location. The EEPI associated with this (which could either be outflowing of hybrid -- see references in last section below) incorrectly corresponds to the more eccentric eye position.

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[5]The direction of the perceived median plane is equal to $-I$, and

$$I = (k - 1)\,\alpha. \quad (1)$$

At the limiting direction of gaze, α_m, I is at its maximum I_m, and

$$I_m = (k - 1)\,\alpha_m. \quad (2)$$

We have found k and α_m to vary inversely; if we assume that this relation is a power function, then

$$\alpha_m = \alpha_{m_o} / k^n \quad (3)$$

where α_m is the limit of gaze for the normal, unparalyzed eye. Substituting (3) in (2) we have:

$$I_m = k^{(1-n)} \cdot \alpha_{m_o} - \alpha_m \quad (4)$$

{and noting from (3) that for any n, when $k = 1$, $\alpha_m = \alpha_{m_o}$; for $k \rightarrow \infty$, $\alpha_m \rightarrow 0$ }, from (4)

$$\lim_{k \to \infty} I_m \begin{Bmatrix} \infty & ; n < 1 \\ \alpha_{m_o} & ; n = 1 \\ 0 & ; n > 1 \end{Bmatrix}$$

Thus as n varies the three different limiting functions near zero values of α_m can be approximated: the dotted line with $n < 1$, the dashed line with $n = 1$, the dot-dashed line with $n > 1$. Although the relation of α_m to k may not be a power function, most useful functions can be approximated by a power series for which (3) is the first term. By fitting the relation of α_m and k in the partially paralyzed state with the power function we may better predict how it will behave under total paralysis ($\alpha_m = 0$).

ILLUMINATION VS. DARKNESS

Of considerable interest is the fact that the entire illusion of visual localization under paralysis is present only in darkness. In normal illumination, visual localization is entirely accurate. It is likely that accuracy in visually localizing the median plane is based on the curarized observer's ability to see his own body and visually locate the target relative to this view. However, simply seeing his body would not be sufficient to correctly localize the eye-level horizontal. Nor would seeing the entire room per se necessarily produce correct localization of eye-level horizontal. The room could be differently tilted relative to gravity than it was in fact, and this would then require a setting that was differently related to the main lines of organization of the room as available to vision. <u>The visible presence of the room must have influenced and determined the setting of visually perceived eye-level horizontal in a marked way.</u>

We have not yet explored these views regarding the influence of room illumination and of sight of the body on visual localization although experiments to do so are in progress. We have dealt with prior issues. Under partial paralysis visual localization based on the view of the illuminated room (including sight of the body) was entirely different than visual localization based on an EEPI-driven cancellation mechanism as described above. In order to be accurate in room illumination, the localization information from the cancellation mechanism must have been either suppressed or modified. This raises an

important question: Was EEPI itself suppressed or was the information from the cancellation mechanism suppressed? This question is clearly answered by the experiments in the next section.

AUDITORY/VISUAL MATCHES

Two facts gave us the tool with which to deal with the question stated at the end of the previous section: Was EEPI suppressed or was information from the cancellation mechanism suppressed?

(1) Audition is a modality that itself was not influenced by the curare. Curare passes the blood/brain barrier in only miniscule amounts (Matteo, Pua, Khambatta, and Spector, 1977) since the inner ear lies within this barrier it remains unaffected. Although the auditory muscles are affected this has an effect on audition which is very likely to be small and symmetrical and hence uninvolved in auditory localization. In any case, we directly determined auditory localization in our curarized subjects by requiring them to select an auditory stimulus that appeared to lie in the median plane from a horizontal array of 25 (Fig. 5) loudspeakers.

Fig. 5

The choice was entirely unaffected by curare. In addition we employed a "name the speaker" technique in which the subject

reported the "number" of the speaker ("1" - "25"). The pattern of accurate reports and errors made by the partially-paralyzed observer was indistinguishable from the pattern made when he was in the normal, unparalyzed state, although the pattern was different for different individuals.

(2) The normal, uncurarized individual is able to match the location of a sound and light with good accuracy and a reliability of about 2°. Some results are displayed in Figs. 2c and 2f.

Figs. 2c and 2f display the errors in matching the light to the sound as a function of horizontal gaze eccentricity in darkness. It is clear that for the partially paralyzed observer very substantial errors in matching occur, and that these errors are linearly related to gaze eccentricity: For any given departure of gaze from the NID (determined by the location of the fixated light) the observer matched the light to a sound source that was even more eccentrically placed. This error increased with departure in each direction from the NID. In subsequent experiments we determined further that for any given level of curarization the errors in auditory/visual matching were indistinguishable from the errors in visual localization of the median plane alone as described in earlier sections.

Most important in answering the question presently at issue here (what was suppressed?) however, was the fact that the errors of the curarized observer in matching a sound to a light were identical whether normal room illumination was present or whether the match occurred in total darkness. This identity is a

consequence of the elimination of the fact that our procedure eliminated the normal capture of auditory localization by visual context, the elimination derived from the fact that the observer had no visual information regarding which of the 25 loudspeakers produced the sound. Where visual capture was present auditory localization of the curarized observer was as controlled by it as for an uncurarized observer. For example, regardless of gaze eccentricity, the paralyzed observer localized the source of speech from the experimenter as emanating from the experimenter's mouth.

EEPI AND CANCELLATION NOT SUPPRESSED IN ILLUMINATION; VISUAL LOCALIZATION ONLY GUIDED BY CANCELLATION IN DARKNESS

The fact that the auditory/visual matches are identical in room illumination and in darkness and that the errors are substantial indicates that neither EEPI nor the output of the EEPI-driven cancellation mechanism was suppressed per se; both EEPI and the output of the EEPI-driven cancellation mechanism were unchanged by the presence or absence of illumination. Further, the function relating errors in the auditory/visual match to gaze eccentricity was the same as the error function for visual localization of the median plane in darkness. These results imply that both errors have the same basis and that the basis lies in the way in which the visual stimuli are processed for visual localization.

A simple interpretation is the following:

(1) In darkness where a single light cannot be visually related to the observer's visual perception of his own body, the

paralyzed observer's overestimation of gaze eccentricity leads to his errors in setting a light to the median plane.

(2) In the presence of normal illumination the observer visually aligns the target light with the visually seen body, and hence is accurate in visually localizing his median plane. This alignment holds for each eccentricity of gaze regardless of how "visual localization is itself differently displaced relative to veridicality" for different gaze directions. But, the phrase in quotes, in fact, refers to a relation that cannot be directly measured by a comparison of locations simultaneously observed by vision alone, since, if the "translation of visual localization" is uniform across the visual field, all purely visual relations are unchanged.

(3) The change in the relation of visual localization to veridicality can be indirectly measured by comparing visual localization to localization by a sense modality whose relation to veridicality is unchanged by both curare and by variations in gaze eccentricity. We have done so using audition.

Thus, although visual localization in normal illumination -- as far as we have measured it -- is uninfluenced by the EEPI-driven cancellation mechanism, we find that the cancellation mechanism is itself intact and available and can be used for intersensory localization. The suppression of the output of EEPI-driven cancellation by visual context is thus specific to its use for visual localization.

A PARADOX AND ITS RESOLUTION

Although the interpretation of our results so far follows in

a reasonably straightforward way from the measurements, an extremely interesting problem regarding the observations in normal illumination remains for our further exploration. While the solution we present below is probably correct it is not the only possible solution.

Fig.6

To fix ideas consider the case in which the partially paralyzed observer fixates a visual target to the left of his median plane (point F) (Fig.6): (a) As described above when setting a light to his visually perceived median plane he does so accurately in normal illumination (setting to point A) but with a systematic error in darkness (setting to point D). (b) When choosing the loudspeaker whose perceived horizontal location matches the perceived horizontal location of the fixation target he makes the same systemtic error in darkness and in normal illumination (loudspeaker at C chosen to match fixation light at F with distance AD approximately equal to distance CF). (c) In addition, when the observer chooses the loudspeaker that sounds as if it is in his median plane he accurately chooses the speaker at A in both darkness and in normal illumination.

Thus, a paradox exists, and may be stated in either of two essentially equivalent ways: (a) In normal illumination the partially paralyzed observer says that a sound whose location appears to match the location of a light that is visuallly

localized in his median plane (e.g., sound at B matched to light at A) is not itself auditorily localized in his median plane. (b) In normal illumination the partially paralyzed observer says that a sound that is auditorily localized in his median plane is matched in location to a light that does not visually appear to lie in his median plane (e.g., sound at A matched to light at D).

The resolution of the paradox follows directly from the interpretation given earlier: In normal illumination the visual median plane is perceived relative to the visual field of view, and the auditory judgment is not influenced by the visual field since visual capture for the loudspeakers was eliminated. Hence the auditory median plane and the visual median plane are both set correctly. However the EEPI-driven cancellation mechanism has shifted the entire visual coordinate structure relative to the auditory coordinates, leading to gaze-dependent errors in auditory/visual matches whose magnitude is uninfluenced by the presence of illumination. It will be desirable in subsequent observations to require the subject to compare auditory and visual median planes themselves in normal illumination. The observer may be able to note the paradox directly.

THE SOURCE OF EEPI

Considerable controversy has occurred regarding whether EEPI derives from outflow, inflow, or hybrid sources (see Matin, 1972, 1976, 1982; Stevens et al 1976 for reviews). The present experiments do not resolve the issue. They do, however, suggest that a simple basis for the confusion that has prevailed in

dealing with the issue lies in the different access that EEPI-driven cancellation mechanisms have to localization in darkness and in normal illumination, and that failure of the previous work to arrive at a simple conclusion is a result of not dealing with this issue. Thus -- following Helmholtz -- it used to be argued that if attempts were made to turn a totally paralyzed eye, outflow theory (EEPI assumed to be derived from fedforward signals) required that an apparent movement be observed in the direction of the attempted eye turn; no apparent movement implied inflow theory. Although Kornmuller's (1930) work with partially immobilized eyes (in which observers saw movement when they made attempts to turn their eyes) was taken to support outflow theory, observers in experiments by Siebeck (1953, 1954) , Stevens et al (1976), and Brindley et al (1976) failed to observe any movement when attempts were made to turn totally paralyzed eyes. Although this appears to argue for an inflow or hybrid theory, no observations were made in total darkness. The results of the experiments described above suggest that if an outflowing or hybrid source of EEPI were involved different observations would obtain in normal illumination from those in darkness. In fact, in one of the reports (Stevens et al. 1976), the totally paralyzed observers noted that when they attempted to turn their eyes there was a feeling that if they were to attempt to touch a given point they would have to reach in a different direction under eccentric gaze than they would if no attempt at eye turn was made. This may be the precursor to the mislocalizationswe have measured and described above.

We are beginning experiments employing total paralysis; these will be carried out in both normally illuminated environments and in darkness and should resolve the question of whether EEPI is from an outflowing or hybrid source. Although the present evidence remains somewhat in favor of an outflow source as it has since Helmholtz first argued for it, this result is not assured by any means.

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LEGEND

Fig.1 Cancellation Theories for visual localization in the presence of eye movements.

Fig.2 Psychophysical localization measurements by observers LM and JS of perceived eye-level-horizontal [(a) and (d)], perceived median plane [(b) and (e)], and auditory/visual matches [(c) and (f)]. Crosses are measurements with uncurarized observers (before paralysis); triangles are measurements during paralysis. Each point is an average of 2 or 3 settings. The two lines through the data in each graph are least square fits.

(a) and (d): In complete darkness the observer fixated a small visible target whose angular elevation with respect to the transverse plane through the head is plotted on the abscissa: this elevation defined the vertical angle of the eye in the head. The transverse plane through the head was itself above the physical horizontal by about 25° for LM and 30° for JS. While maintaining fixation on this first light the subject set a second peripherally-viewed light (which was moveable in the same vertical meridian as the first target) to a height that appeared to be at his eye-level-horizontal -- this latter height is plotted on the ordinate as vertical elevation of perceived horizontal.

(b) and (e): The observer fixated a small visible target in complete darkness whose horizontal deviation from the physical median plane through his body is plotted on the abscissa. This angle defined the horizonal angle of gaze. While maintaining fixation on this first light, the subject instructed the

experimenter to set a second visual target (which was movable in the same horizontal plane as the first target) to the perceived median plane. This latter setting is plotted as the ordinate.

(c) and (f): The observer matched the perceived horizontal location of a sound to that of a fixated light. The abscissa is the physical location of the fixated light with respect to the median plane. The ordinate is the error in the auditory localization of the fixated light -- the difference between the PSE (Point of Subjective Equality) of the auditory localization of the fixated light and the physical location of that light. For both Figs. 2c and 2f room illumination was left on. The results are indistinguishable when the experiment is carried out in total darkness.

(g): The relation between the vertical fixation direction (gaze direction) relative to the head (angle α), the orientation of the head with respect to the physical horizontal (angle β), and the direction of gaze with respect to the physical horizontal (angle γ).

<u>Fig. 3</u> Mislocalizations of the median plane in darkness at two different levels of partial paralysis.

<u>Fig. 4</u> Theoretical functions relating error of visual localization to direction of gaze under various levels of paralysis.

(a) Visually perceived direction of eye-level horizontal as a function of vertical gaze direction.

(b) Visually perceived direction of median plane as a function of horizontal gaze direction.

Illusion magnitude I (used in text) is equal to the negative of the ordinate value. Our uncertainty regarding the outcome around total paralysis (0° range of possible eye movement) is indicated by showing the dotted lines (which suggests that the errors increase asymptotically) and dot-dash lines (which suggests a drop to zero of the localization errors), as well as the dashed lines showing a simple intersection of the limit functions with the 0° abscissa value. (Also see Ftn regarding these asymptotic values.)

Fig. 5 Sketch of spatial relations between observer and stimuli. The observer and fixation lights could be rotated in a horizontal plane around center to meet the needs for measuring illusion magnitude.

Fig. 6 The paradox. See text for description and resolution.

Fig. 1

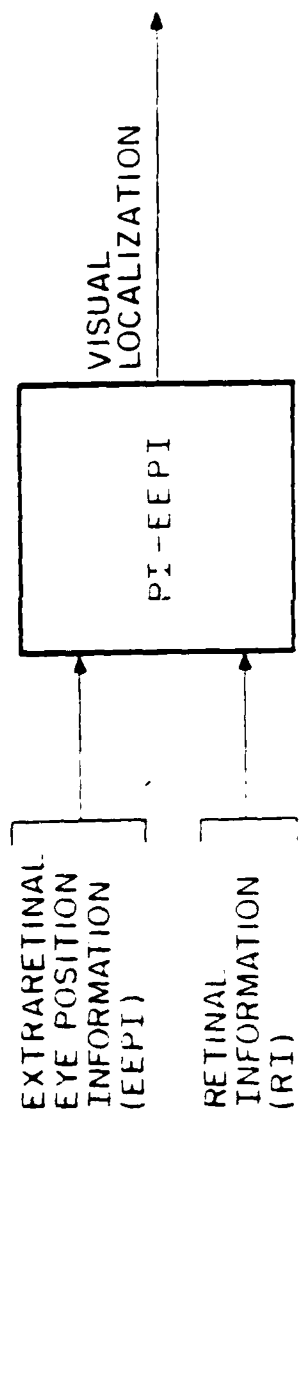

VISUAL
LOCALIZATION
PI-EEPI
EXTRARETINAL
EYE POSITION
INFORMATION
(EEPI)
RETINAL
INFORMATION
(RI)

Fig. 2

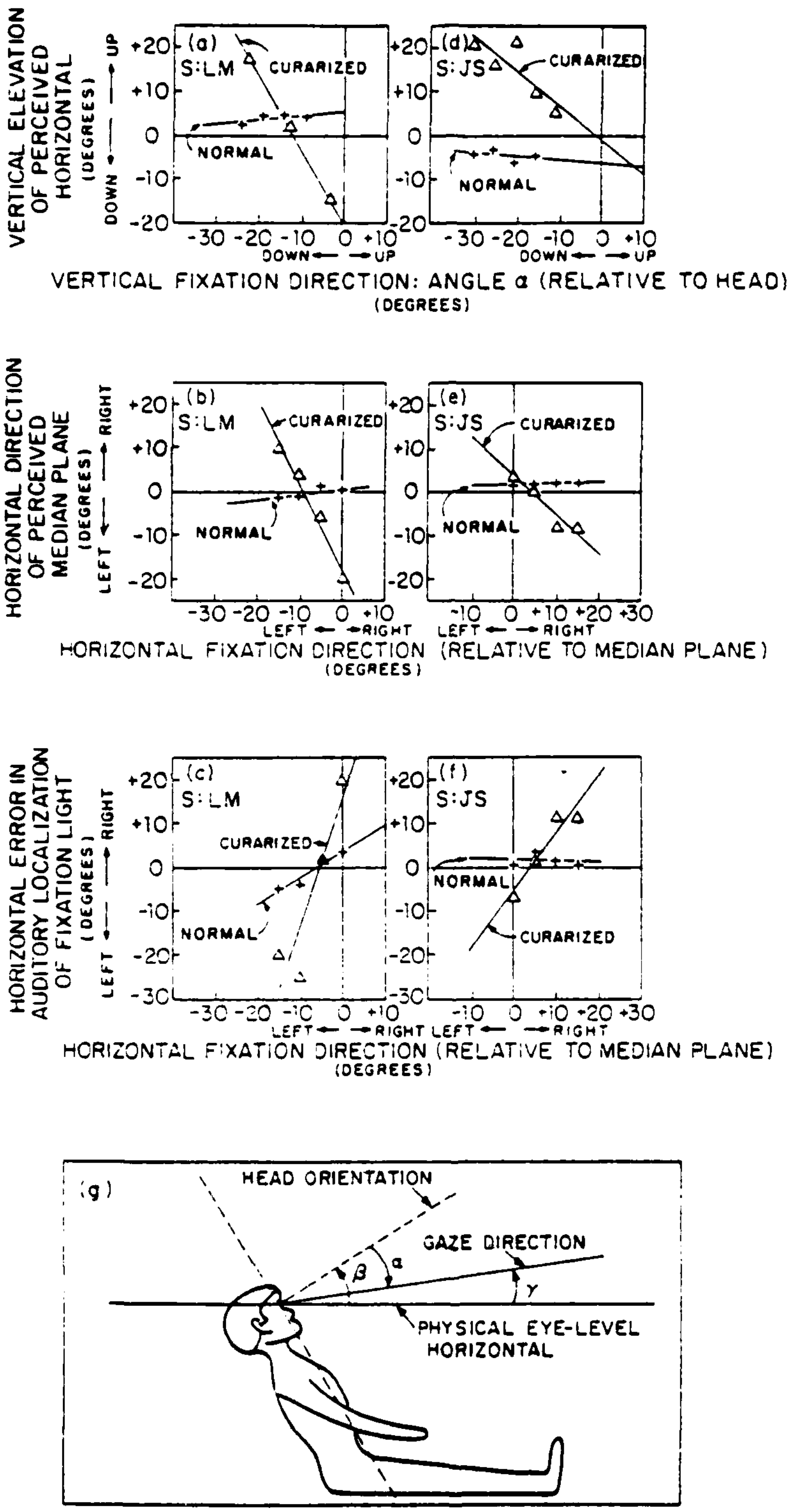
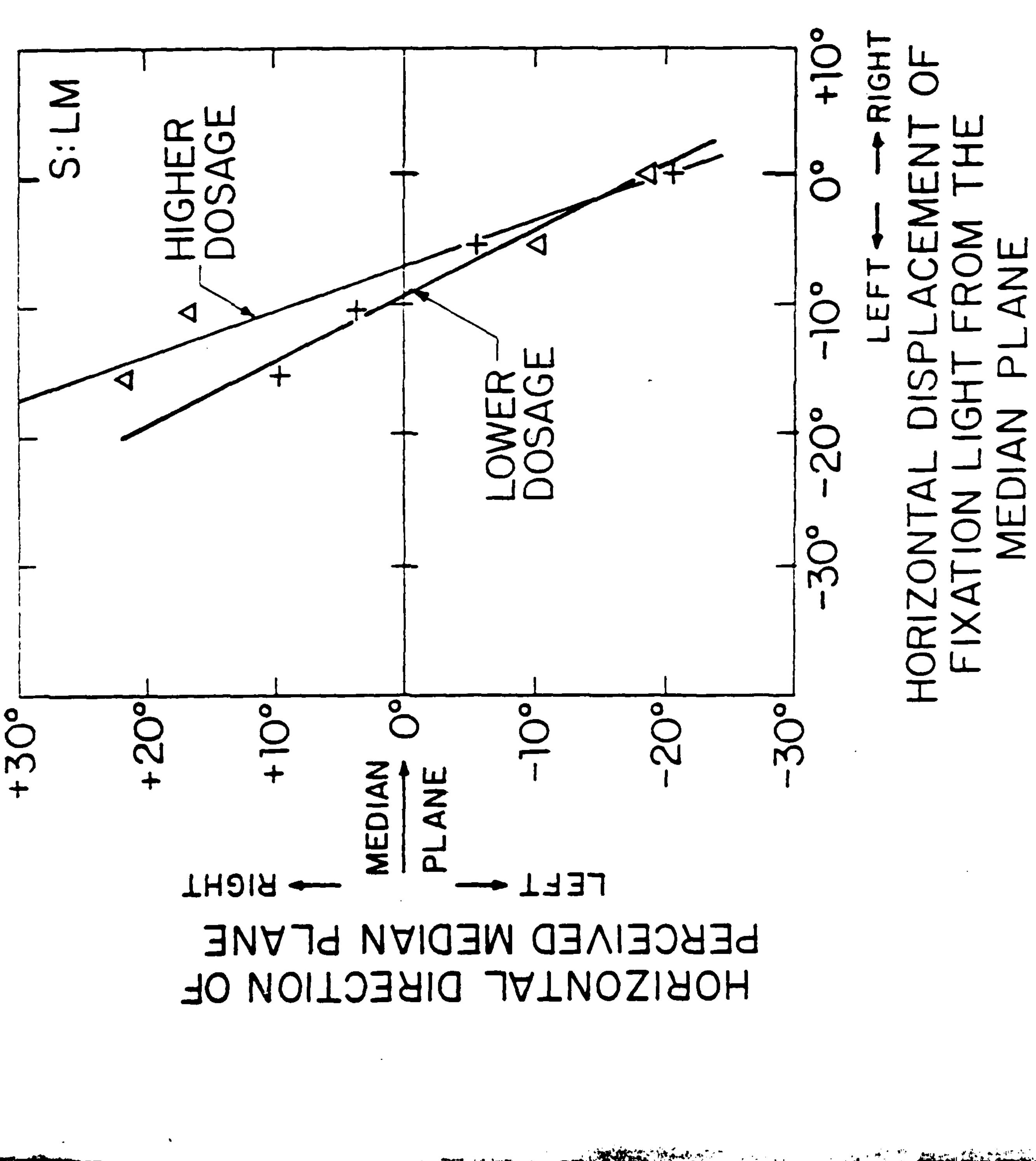
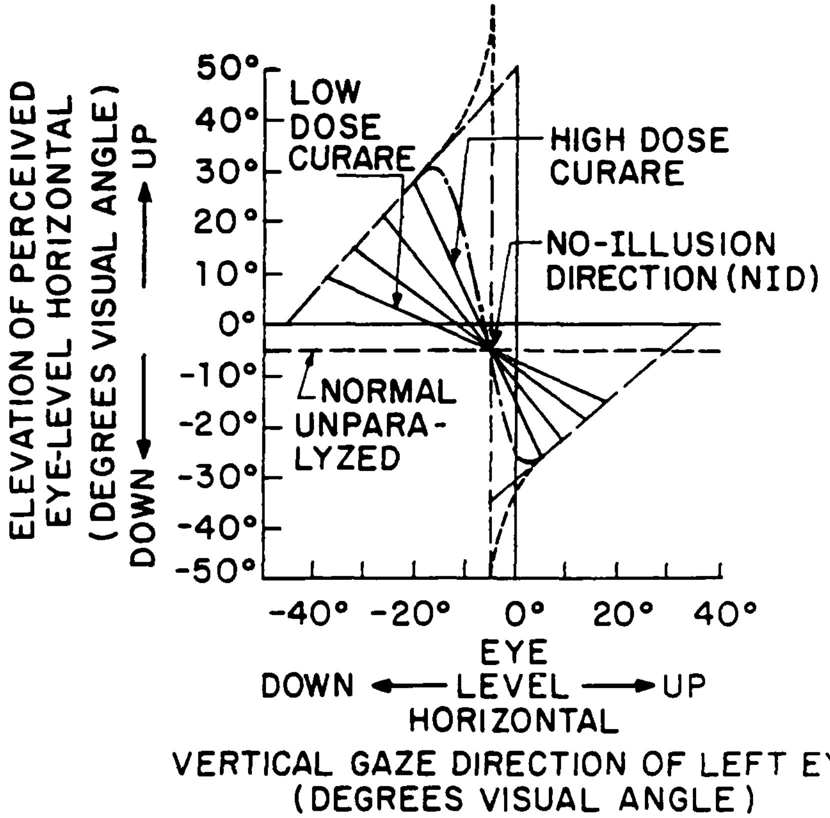
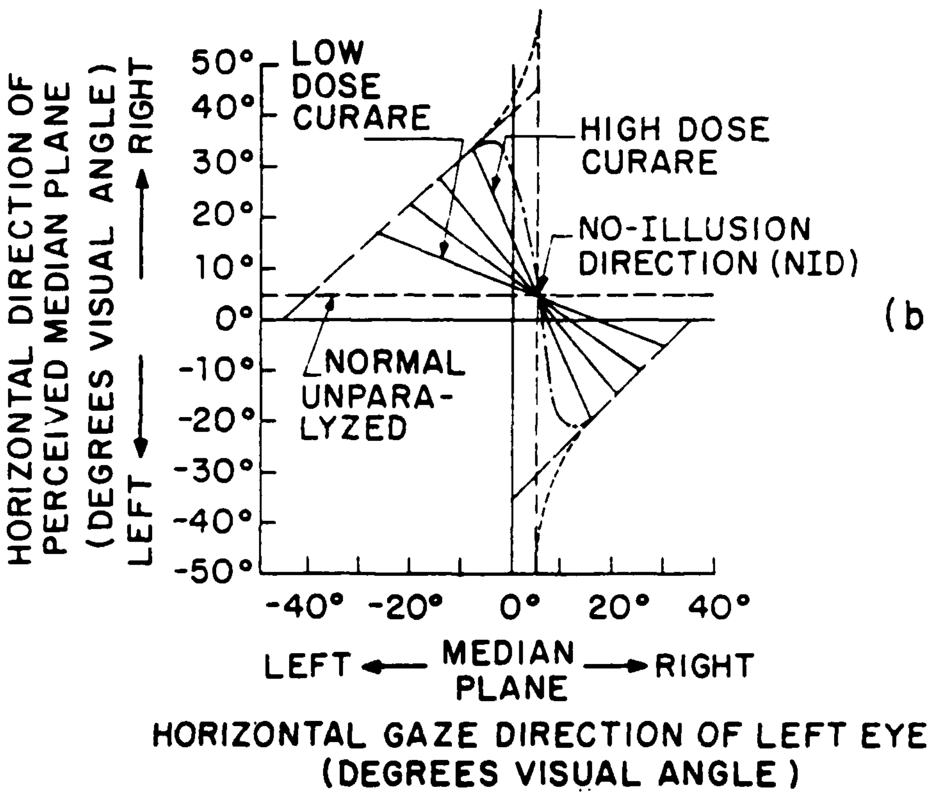

VERTICAL ELEVATION OF PERCEIVED HORIZONTAL (DEGREES)
DOWN UP
(a)
S:LM
CURARIZED
NORMAL
(d)
S:JS
CURARIZED
NORMAL
-30 -20 -10 0 +10
DOWN UP
VERTICAL FIXATION DIRECTION: ANGLE α (RELATIVE TO HEAD) (DEGREES)
HORIZONTAL DIRECTION OF PERCEIVED MEDIAN PLANE (DEGREES)
LEFT RIGHT
(b)
S:LM
CURARIZED
NORMAL
(e)
S:JS
CURARIZED
NORMAL
-10 0 +10 +20 +30
LEFT RIGHT
HORIZONTAL FIXATION DIRECTION (RELATIVE TO MEDIAN PLANE) (DEGREES)
HORIZONTAL ERROR IN AUDITORY LOCALIZATION OF FIXATION LIGHT (DEGREES)
(c)
S:LM
CURARIZED
NORMAL
(f)
S:JS
NORMAL
CURARIZED
HORIZONTAL FIXATION DIRECTION (RELATIVE TO MEDIAN PLANE) (DEGREES)
(g)
HEAD ORIENTATION
GAZE DIRECTION
PHYSICAL EYE-LEVEL HORIZONTAL
β
α
γ

Fig. 3


S: LM
HIGHER DOSAGE
LOWER DOSAGE
+30°
+20°
+10°
0°
-10°
-20°
-30°
-30°
-20°
-10°
0°
+10°
LEFT ← → RIGHT
HORIZONTAL DISPLACEMENT OF FIXATION LIGHT FROM THE MEDIAN PLANE
MEDIAN PLANE
RIGHT
LEFT
HORIZONTAL DIRECTION OF PERCEIVED MEDIAN PLANE

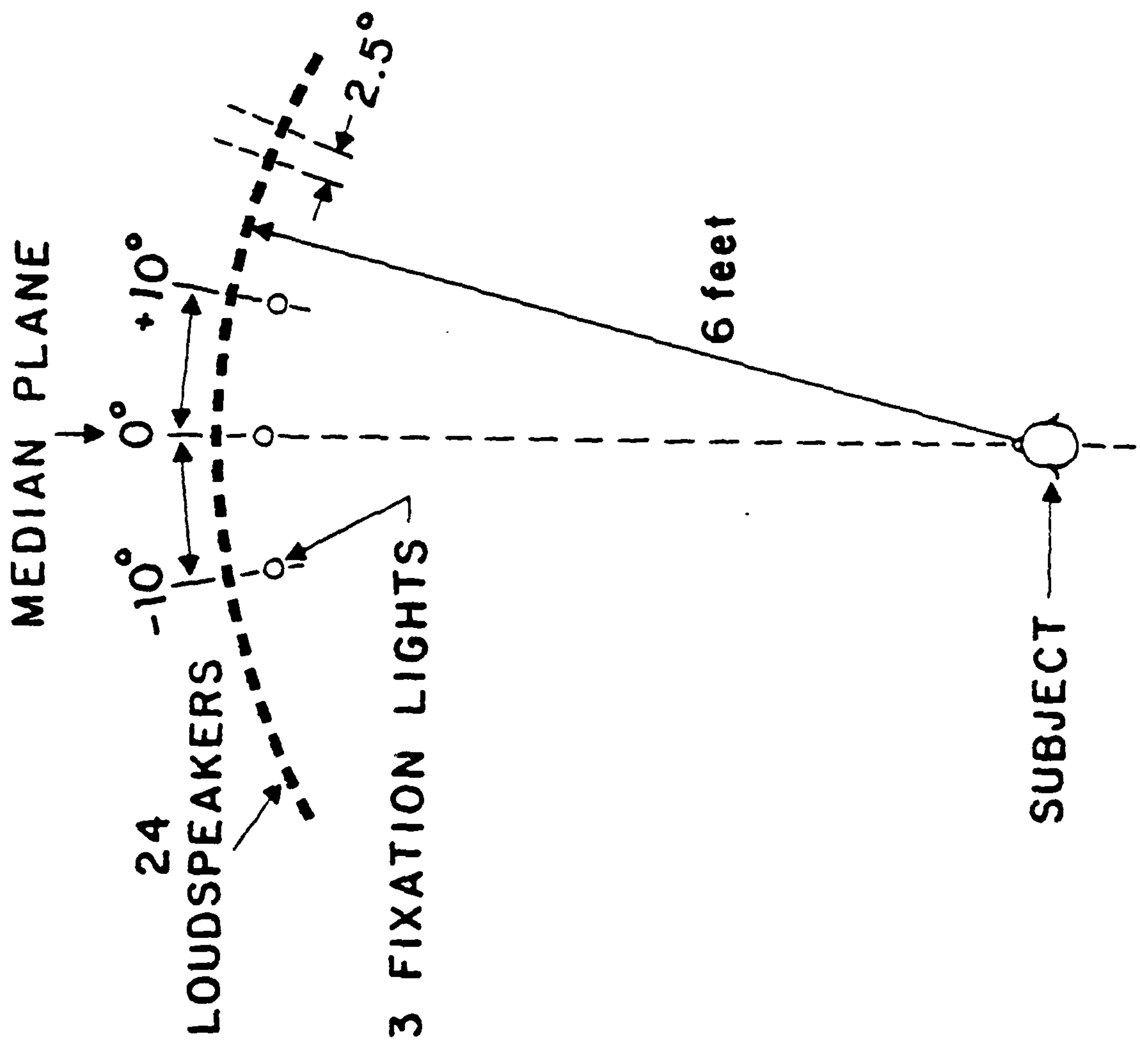

ELEVATION OF PERCEIVED EYE-LEVEL HORIZONTAL (DEGREES VISUAL ANGLE)
DOWN
UP
50°
40°
30°
20°
10°
0°
-10°
-20°
-30°
-40°
-50°
LOW DOSE CURARE
HIGH DOSE CURARE
NO-ILLUSION DIRECTION (NID)
NORMAL UNPARA-LYZED
-40° -20° 0° 20° 40°
DOWN
EYE LEVEL HORIZONTAL
UP
VERTICAL GAZE DIRECTION OF LEFT EYE (DEGREES VISUAL ANGLE)

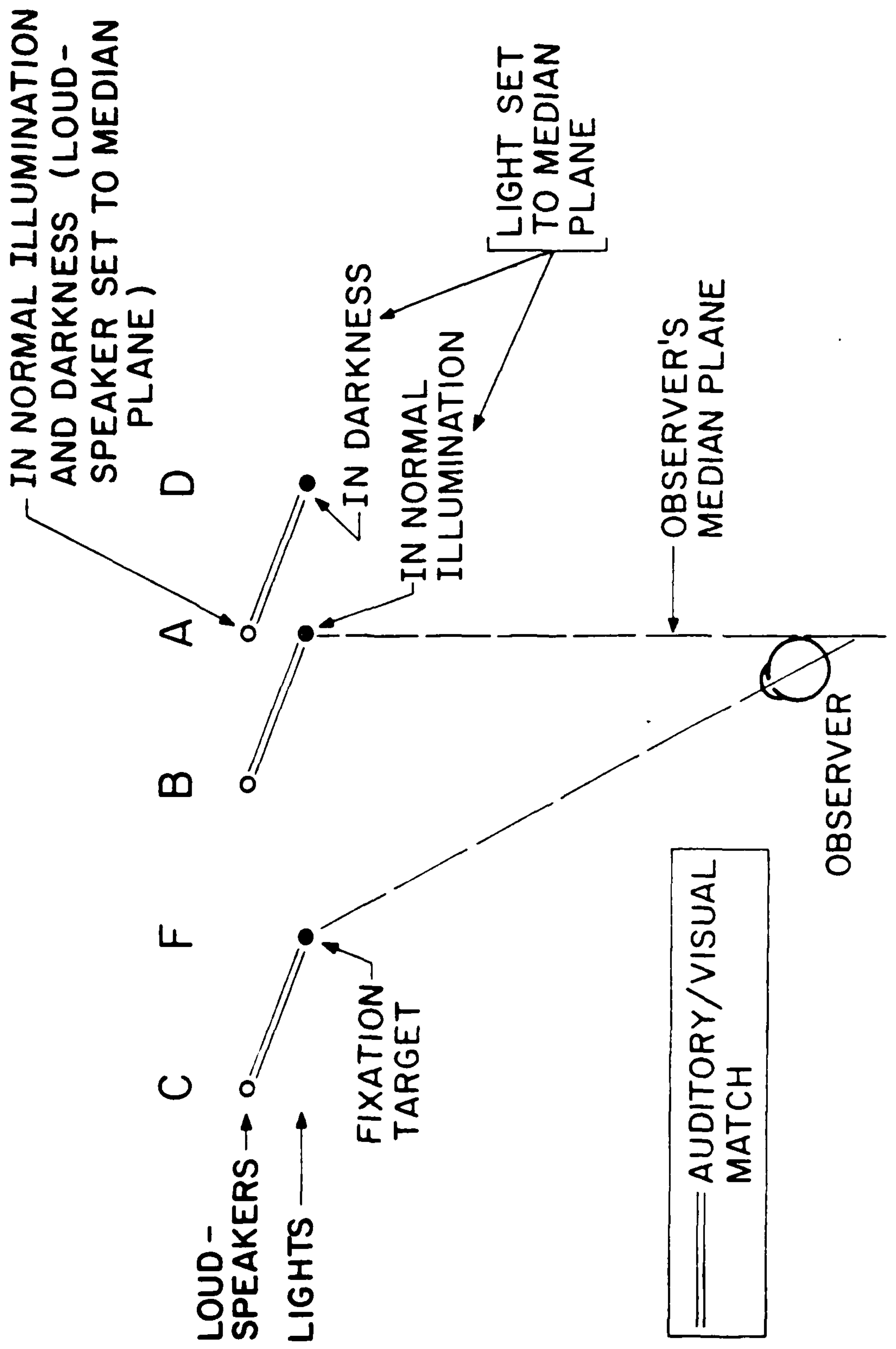
(a)


HORIZONTAL DIRECTION OF PERCEIVED MEDIAN PLANE (DEGREES VISUAL ANGLE)
LEFT
RIGHT
50°
40°
30°
20°
10°
0°
-10°
-20°
-30°
-40°
-50°
LOW DOSE CURARE
HIGH DOSE CURARE
NO-ILLUSION DIRECTION (NID)
NORMAL UNPARA-LYZED
-40° -20° 0° 20° 40°
LEFT
MEDIAN PLANE
RIGHT
HORIZONTAL GAZE DIRECTION OF LEFT EYE (DEGREES VISUAL ANGLE)

(b)

Fig. 5


MEDIAN PLANE
0°
+10°
-10°
2.5°
6 feet
24
LOUDSPEAKERS
3 FIXATION LIGHTS
SUBJECT


IN NORMAL ILLUMINATION AND DARKNESS (LOUD-SPEAKER SET TO MEDIAN PLANE)
LIGHT SET TO MEDIAN PLANE
IN DARKNESS
IN NORMAL ILLUMINATION
IN NORMAL ILLUMINATION
OBSERVER'S MEDIAN PLANE
D
A
B
F
C
LOUD-SPEAKERS
LIGHTS
FIXATION TARGET
OBSERVER
AUDITORY/VISUAL MATCH

ATE
LMED

-8